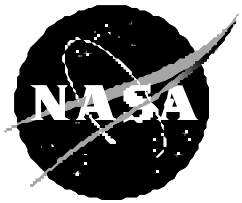


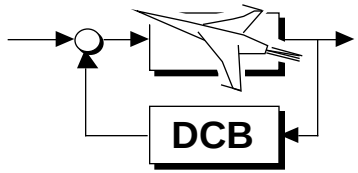


# Robust Multivariable Flutter Suppression for the Benchmark Active Control Technology (BACT) Wind-Tunnel Model

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*Dynamics and Control Branch*

**Eleventh Symposium on Structural Dynamics and Control**
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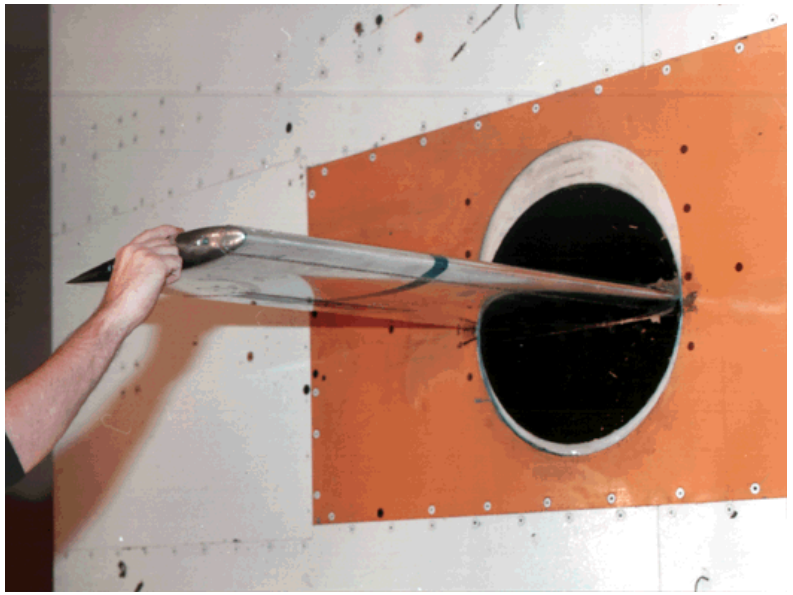
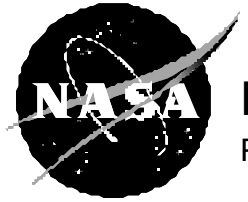
# Outline

- **BACT Overview**
  - **Program**
  - **Wind-Tunnel Model**
- **Control Design**
  - **Design Model**
  - **Design Objectives**
  - **Robust Multivariable Designs**
- **Experimental Results**
- **Concluding Remarks**



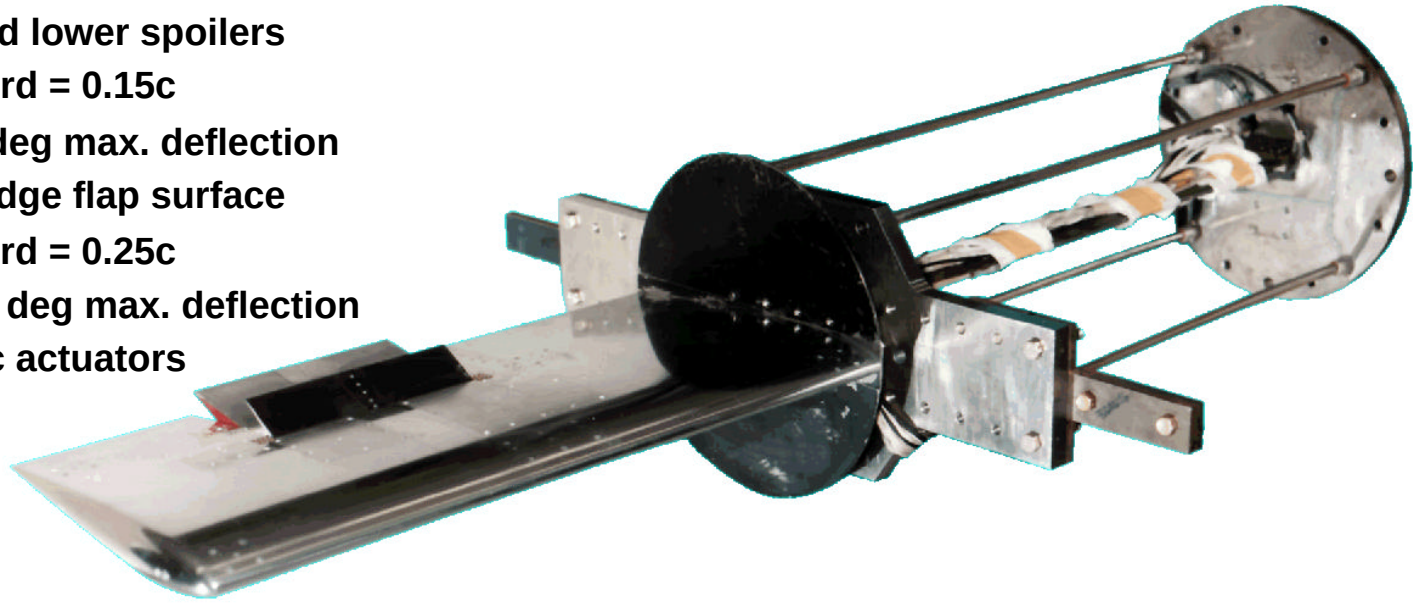
# BACT Program Overview

- **Benchmark Aeroelastic Models Program**
  - **study physics of aeroelastic phenomena**
    - » **classical transonic flutter "bucket"**
    - » **shock induced instabilities**
    - » **dynamic vortex-structure interaction**
  - **data to validate steady and unsteady aero codes**
  - **active control of aeroelastic systems**
- **Benchmark Active Control Technology (BACT)**
  - **high quality unsteady aero data near flutter**
  - **active flutter suppression**
    - » **innovative control concepts - spoilers and multiple effectors**
    - » **innovative design methods - H∞, μ-synthesis, neural nets**
  - **validate on-line controller performance evaluation tool**



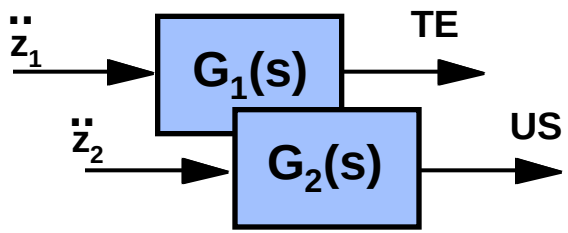
# BACT System Overview

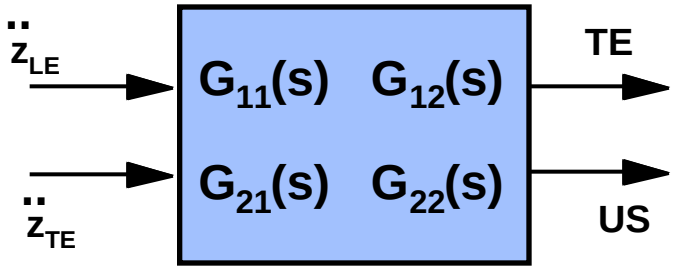
- **Pitch and Plunge Apparatus (PAPA)**
  - **2-DOF : pitch and plunge**
  - **5-6 deg max. rotation**
  - **1.5 inch max. deflection**
- **Wind-Tunnel Model**
  - **rigid NACA 0012 airfoil**
  - **AR = 2 (c = 16 in., b = 32 in.)**
- **Control Surfaces**
  - **span = 0.3b, centered at 0.6b**
  - **upper and lower spoilers**
    - » **chord = 0.15c**
    - » **45 deg max. deflection**
  - **trailing edge flap surface**
    - » **chord = 0.25c**
    - » **±15 deg max. deflection**
  - **hydraulic actuators**
- **Instrumentation**
  - **4 accelerometers in corners of wing**
  - **pitch angle sensors**
  - **70 pressure transducers**
    - » **58 @ 0.6b (incl. control surfaces)**
    - » **17 @ 0.4b**
  - **add'l transducers on splitter plate**
  - **accels and strain gauges on PAPA**



# Flutter Suppression Control Laws

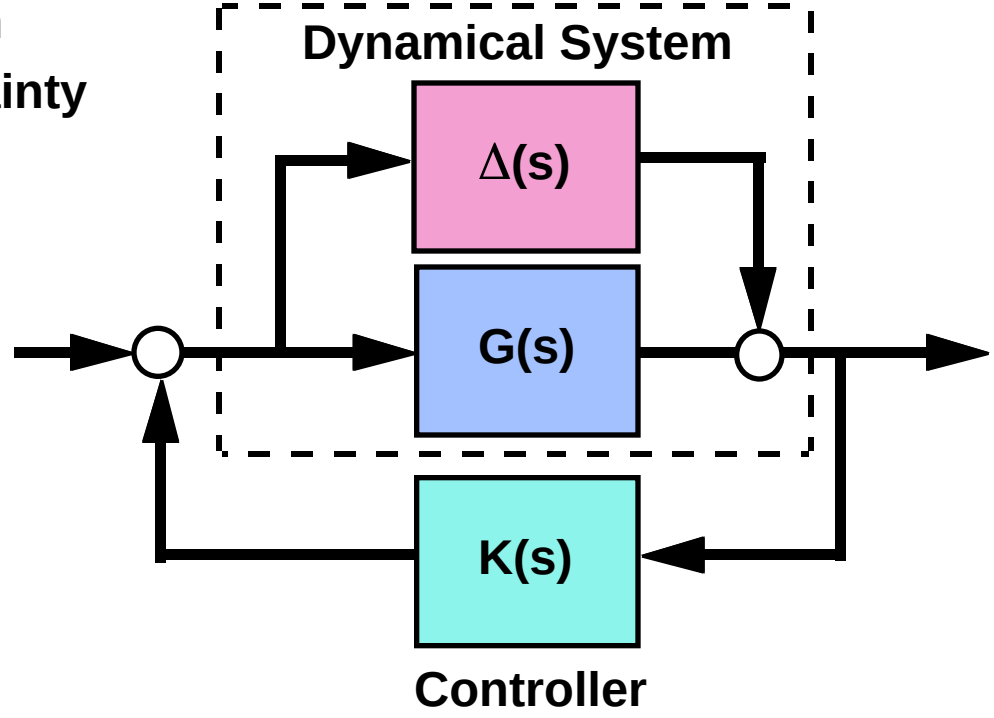
- **Design Objectives**
  - **Stability Over Entire Operating Range**
  - **Acceptable Control Activity**
  - **Simple Implementation**
- **Traditionally Designed SISO Controllers**
  - **Demonstrate Flutter Suppression Using *Spoilers***
  - **Develop Performance Specifications**
  - **Coupled SISO Controllers**
- **Robust MIMO Controllers**
  - **Demonstrate Multivariable Flutter Suppression**
  - **Evaluate Enhanced Robustness Properties**



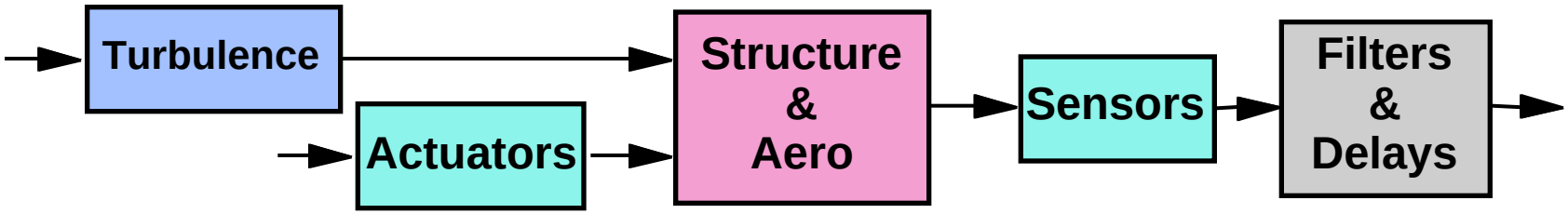
# MIMO Controller Design Methods

- **Robustness**
  - **Maintain Stability and Performance Subject to Model Variation**
  - **Variations Include**
    - » **Operating Condition**
    - » **Model Error/Uncertainty**
- **H∞ Control**
  - **Robust Stability**
  - **Nominal Performance**
- **μ-Synthesis**
  - **Robust Stability**
  - **Robust Performance**
  - **Structured Uncertainty**

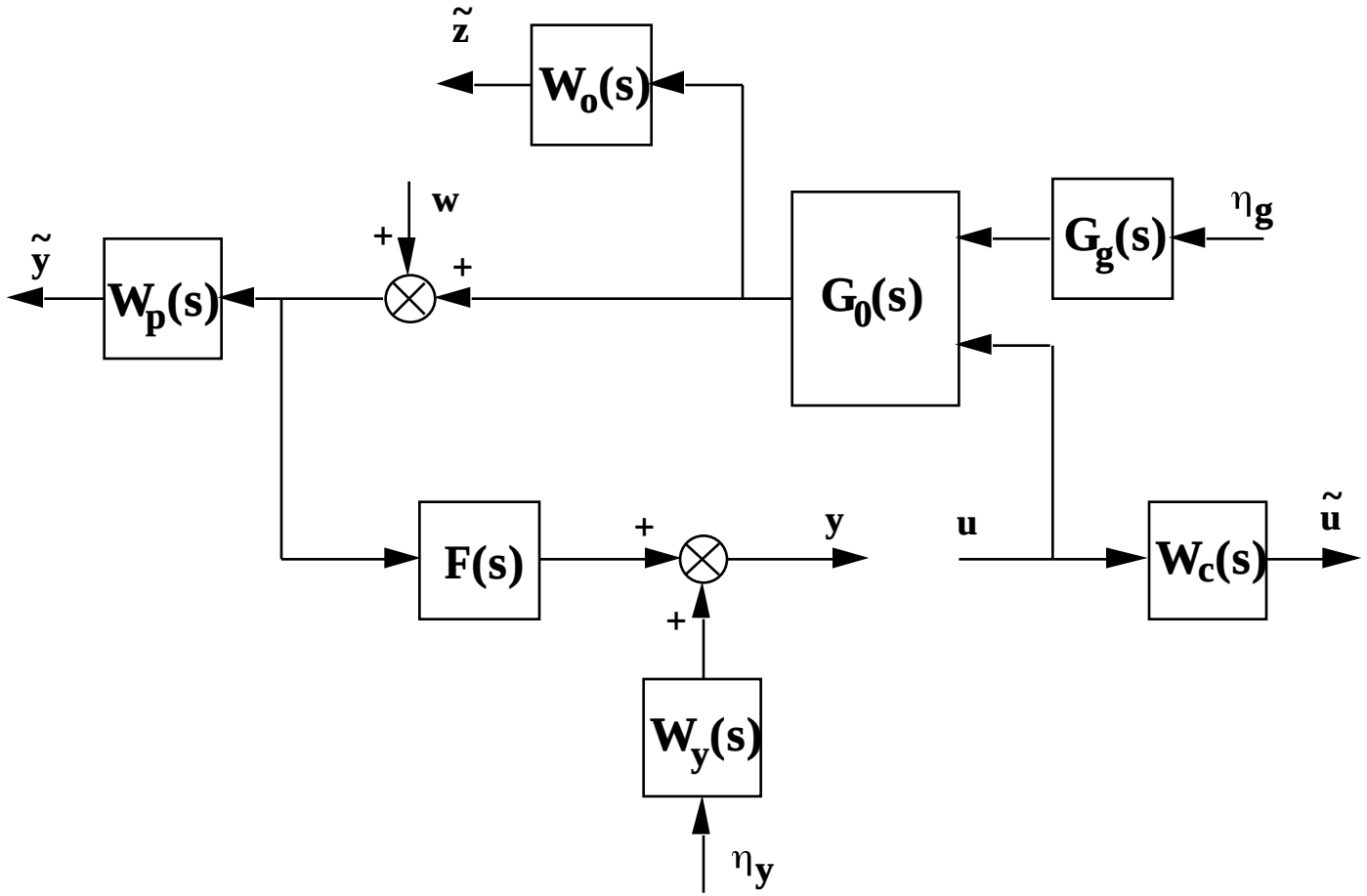


# Modeling for Flutter Suppression

- **Model elements**
  - **structural dynamics**
  - **steady and unsteady aerodynamics (including control effects)**
  - **turbulence effects**
  - **actuators, sensors, controller effects**

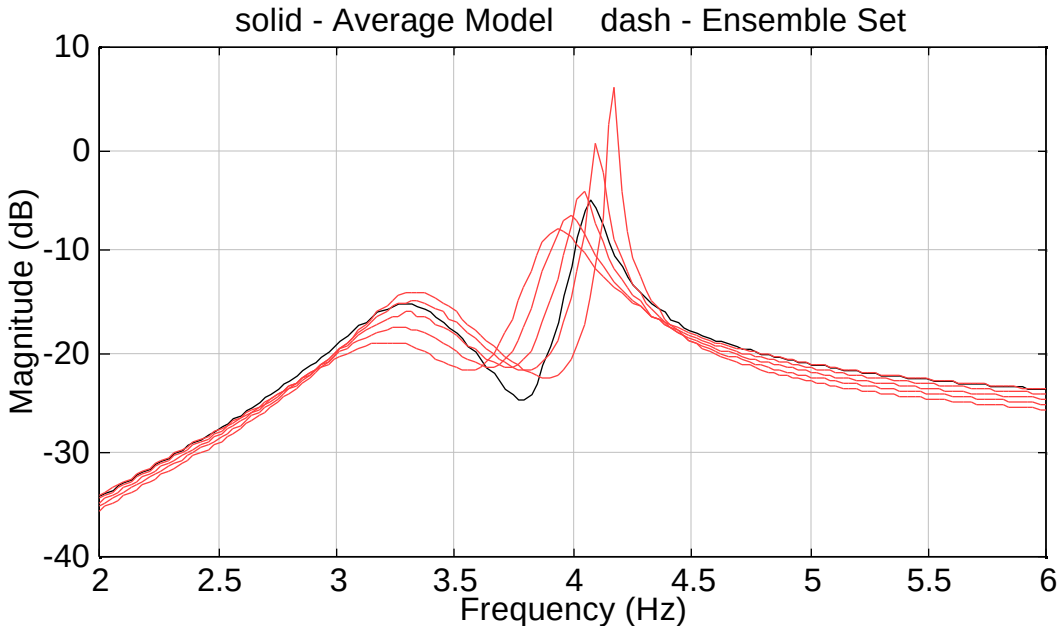


# P-Δ Model



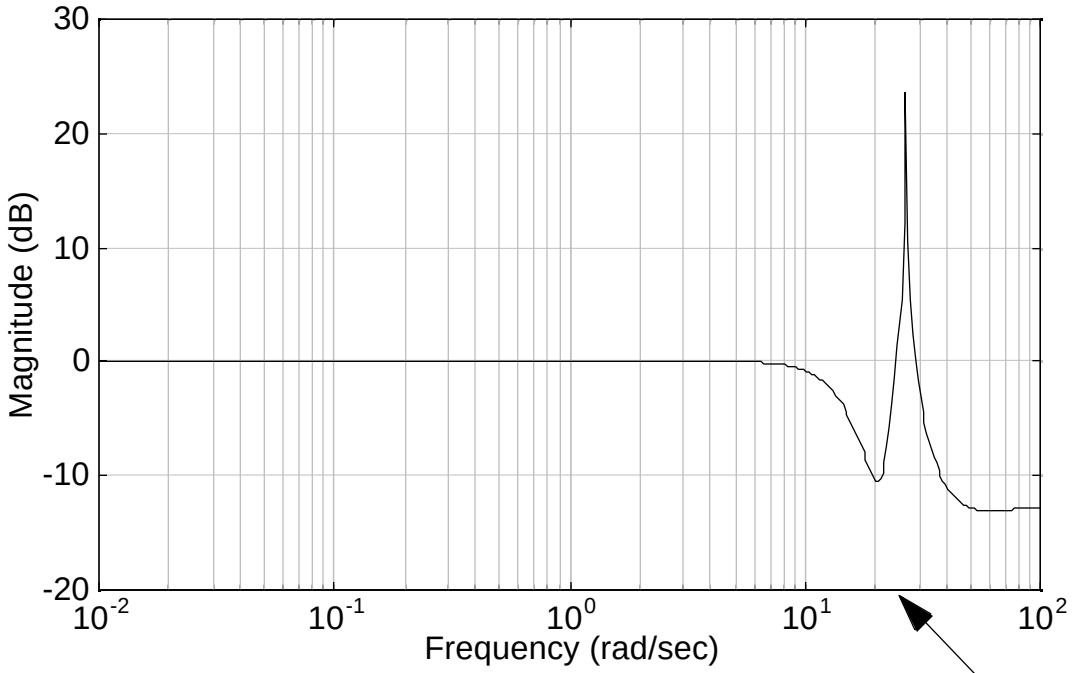
# Plant Model

- **Averaged over unstable conditions (q=155-195 psf)**
- **Frequency weighted internally balanced reduction**



# Uncertainty Model

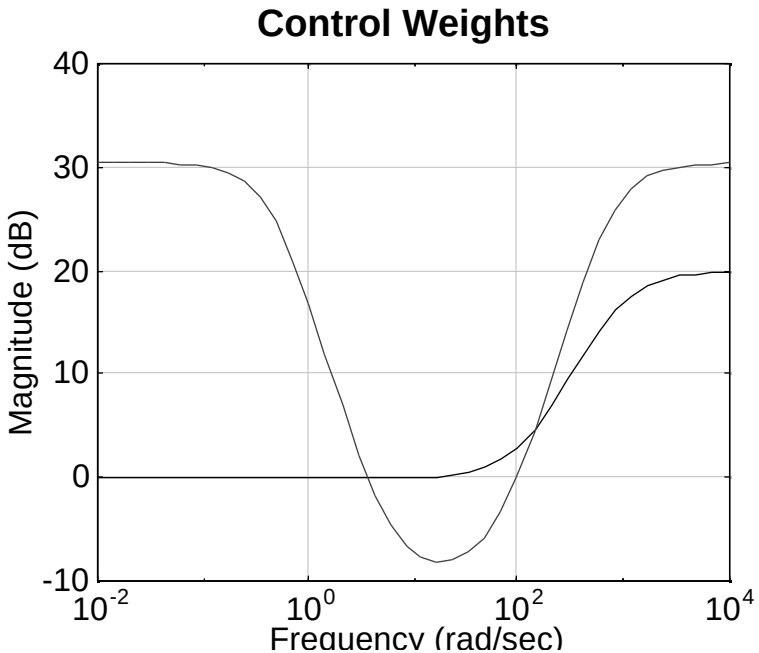
- **Based on reduced averaged model and ensemble**
- **Output multiplicative form**

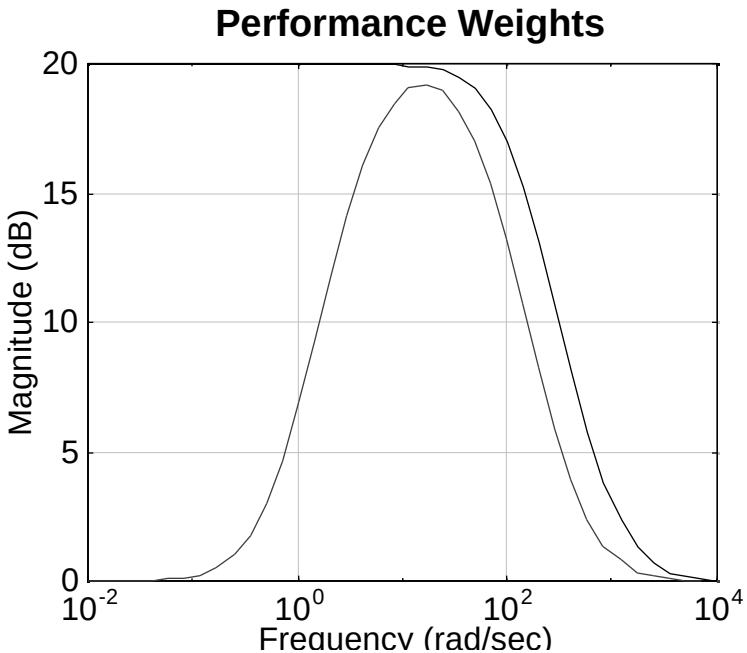



**Flutter Frequency**

# Weighting Functions

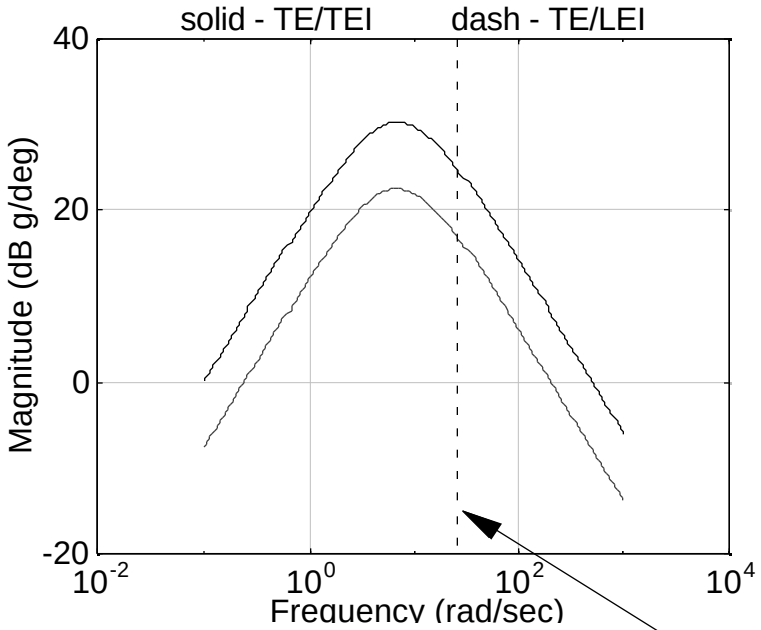
- **Performance :** $\max\left(\ddot{\theta}, \ddot{h}\right) < 0.01g$
- **Control :** $\max\left(\delta_{TE}, \delta_{US}\right) < 1.0\,\text{deg} \quad (3.0\,\text{deg})$
- **Output :** $W_y = 1.0e-4$

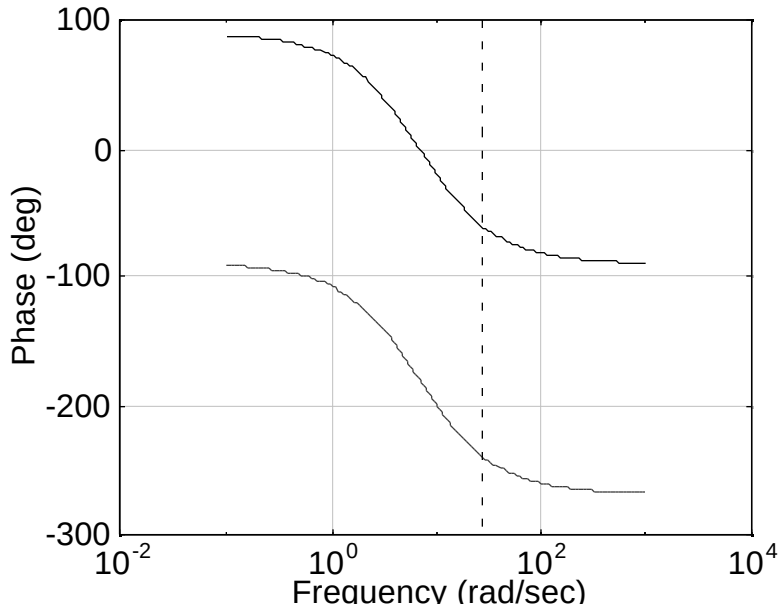


# SISO Control Law

- **Trailing Edge Flap Controller**

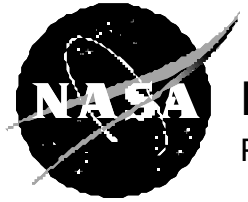



**Flutter Frequency**

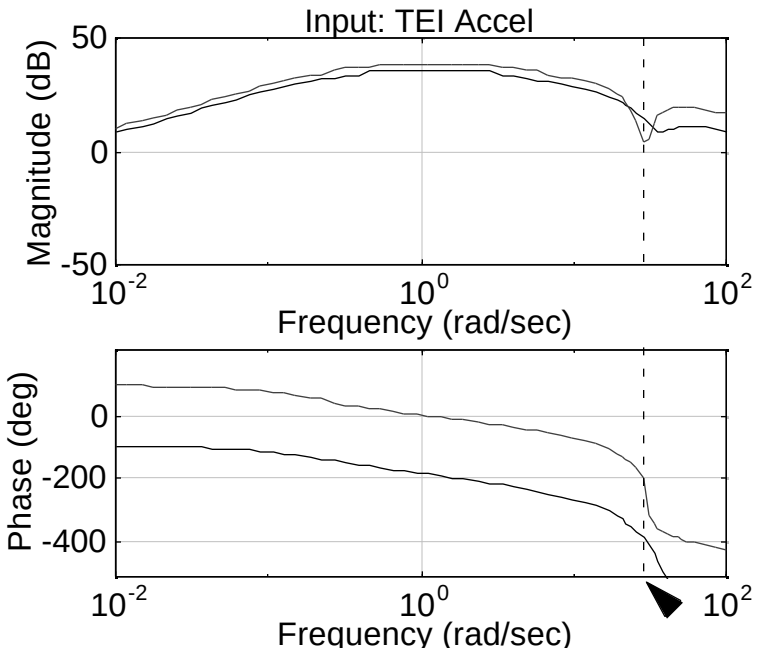
# Design Process

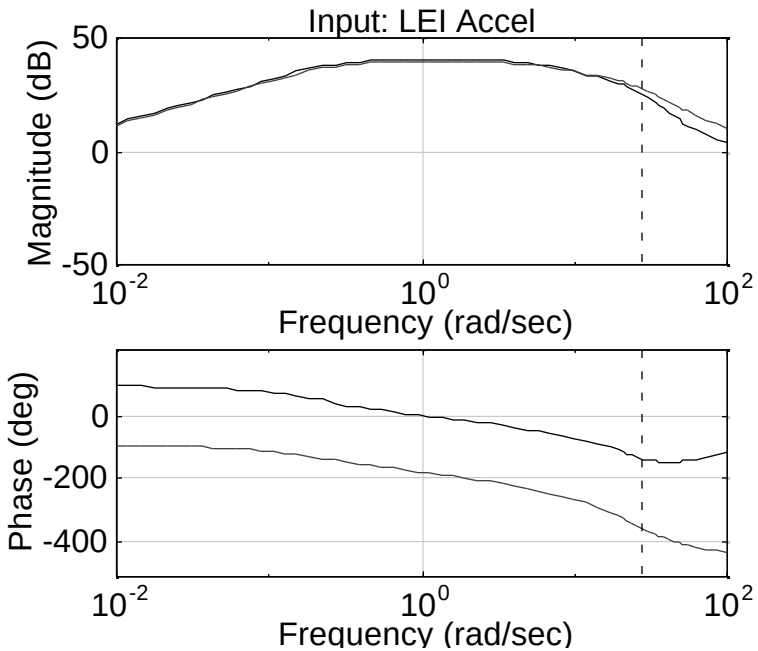
- **Apply design algorithms**
  - **H∞ and μ-synthesis**
  - **Used μ-Analysis and Synthesis Toolbox (for MATLAB)**
- **Reduce controller order**
  - **required order - 24 states (or less)**
  - **frequency weighted internally balanced reduction**
- **Augment washout filters**
  - **low frequency attenuation was insufficient**
  - **significant biases and drift in accelerometer amps**
- **Discretize control law**



# Control Laws

- **H∞ Design #1**

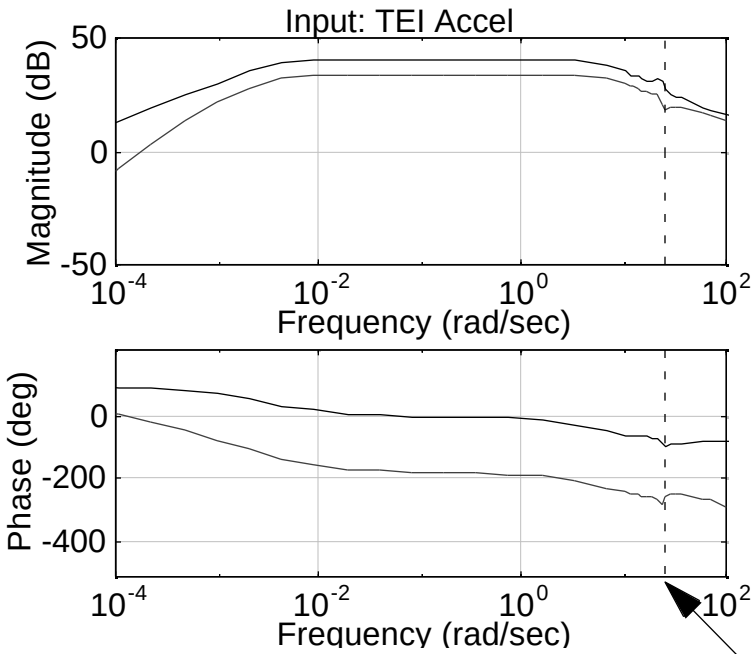


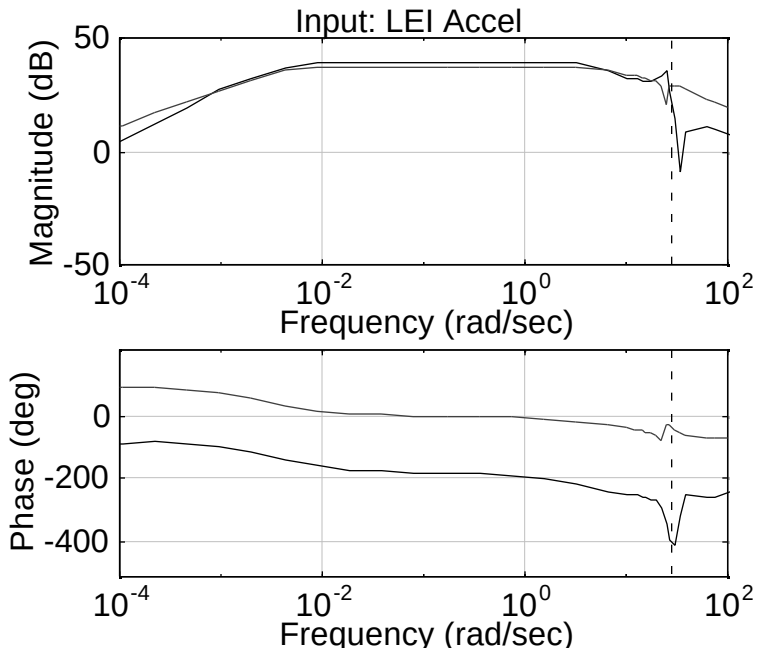




**Flutter Frequency**

# Control Laws

- **μ-Synthesis Design #1**

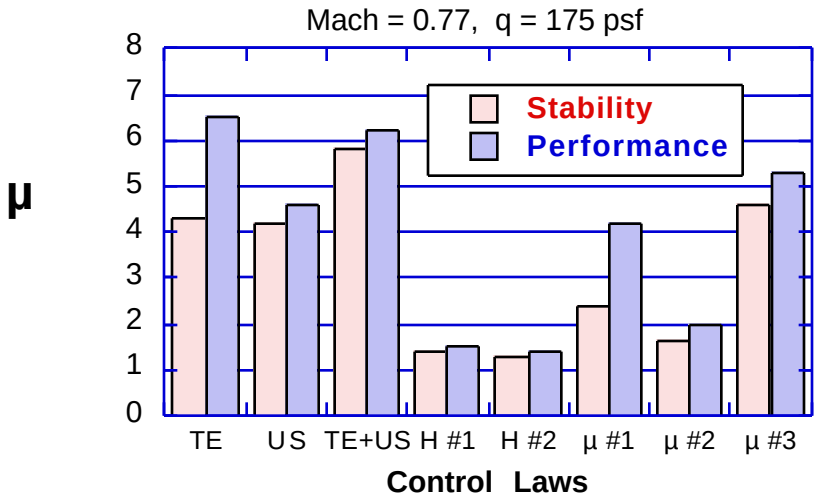


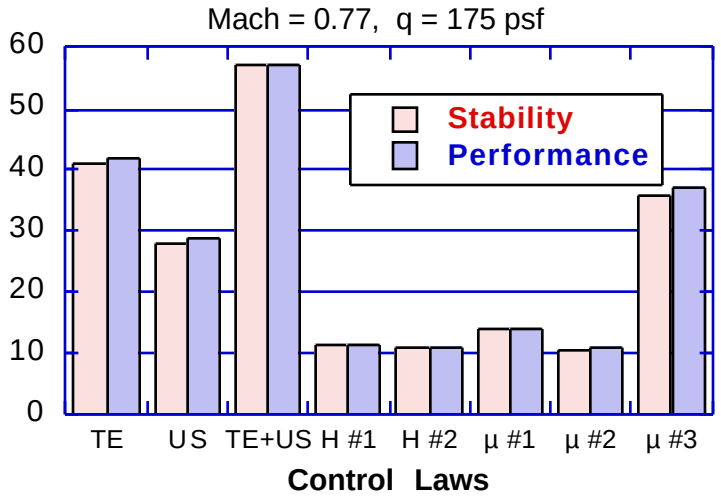

**Flutter Frequency**

# Robustness Analysis

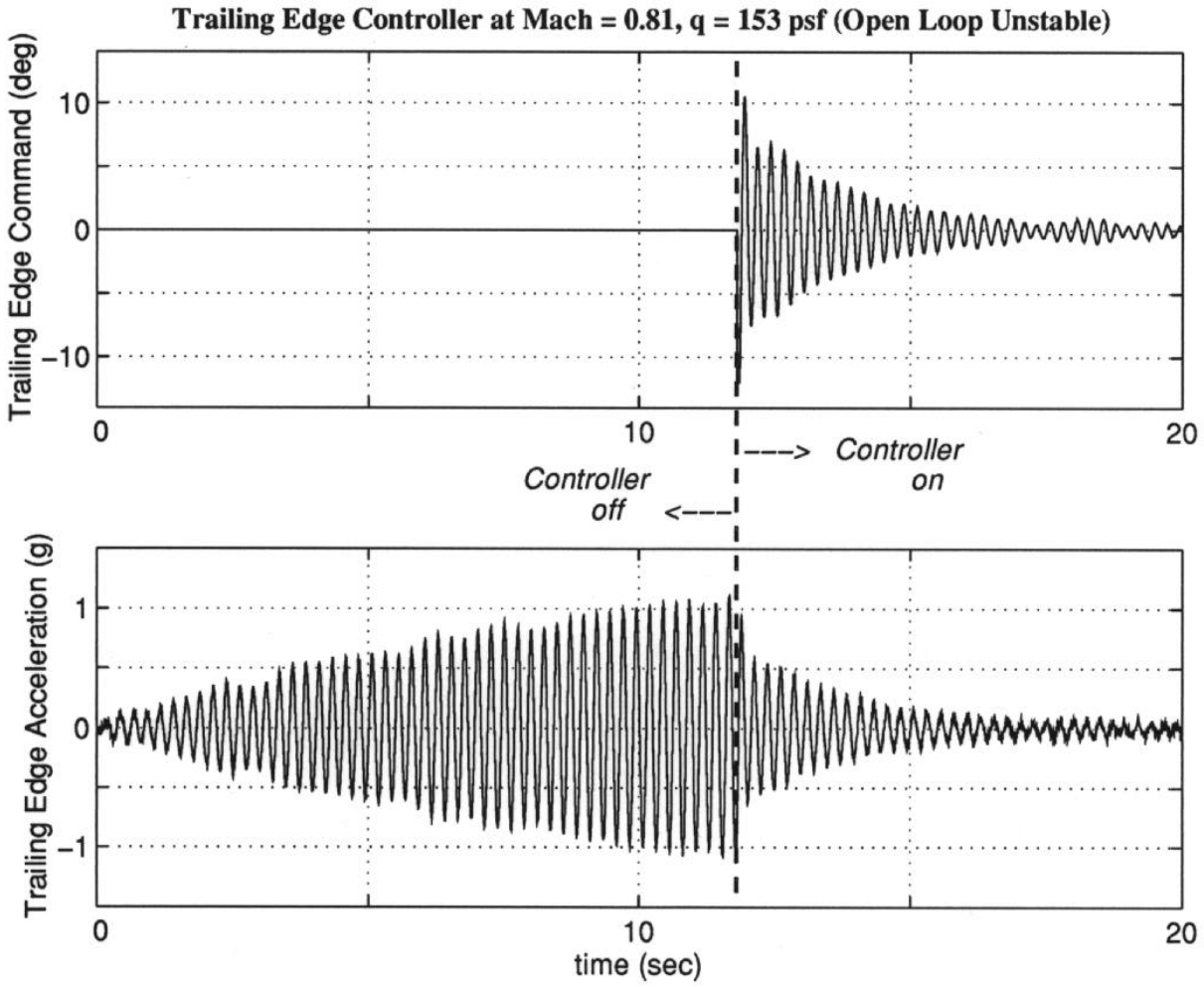
- **"Unit" Uncertainty**



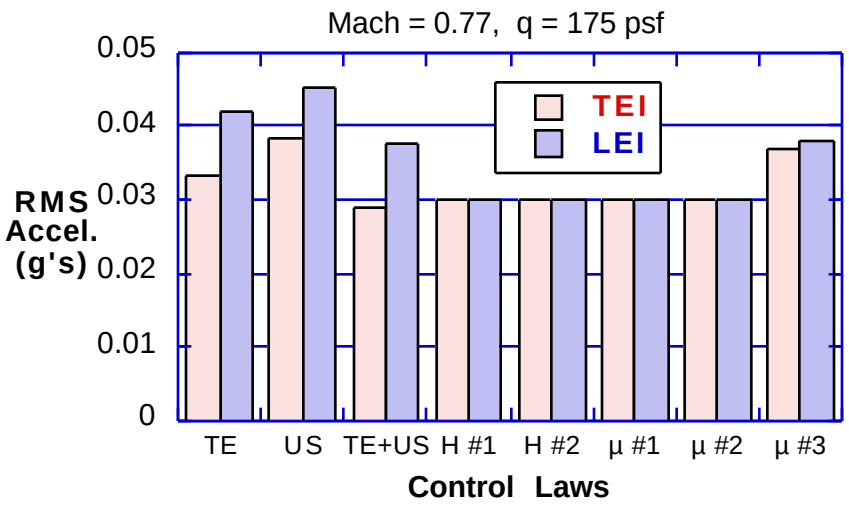

- **"Average" Uncertainty**

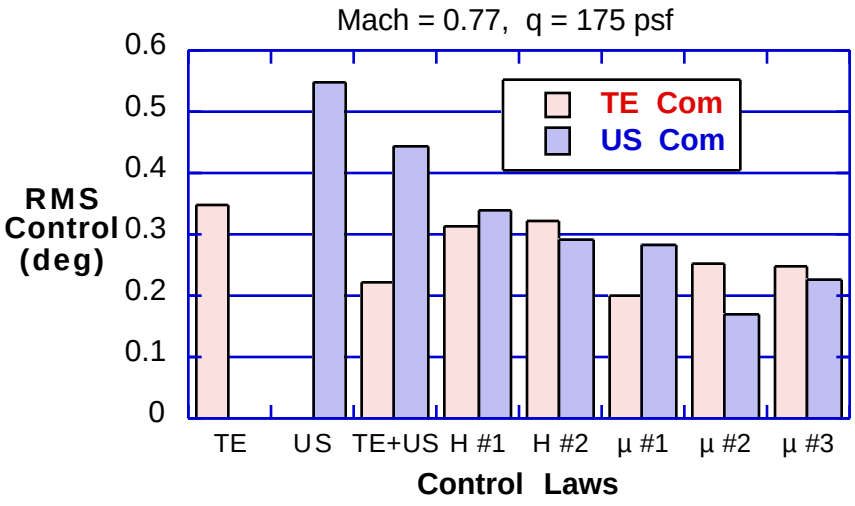


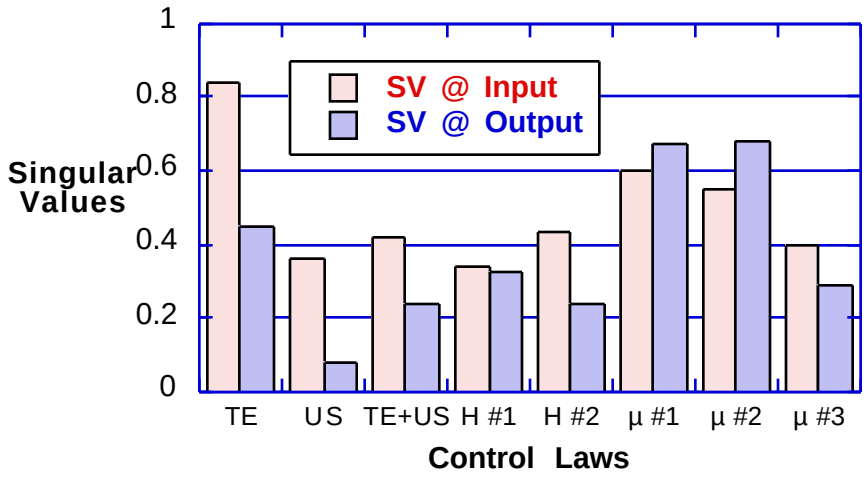
# Transient Response - Example



# Experimental Results



# Concluding Remarks

- **Spoilers for Flutter Suppression**
  - **Representative of "Innovative Control Effectors"**
  - **Additional Design Freedom**
  - **Enhanced Redundancy**
- **Robust Multivariable Flutter Suppression**
  - **Enhanced Performance (over SISO designs)**
  - **Enhanced Robustness**
- **Design Issues**
  - **Difficulty Accomodating Washout Filters**
  - **Difficulty Accomodating Model Order Limitations**
  - **Sensitivity to Performance Specifications**
  - **Numerical Algorithms and Convergence Issues**